Dearborn, Michigan
NOISE-CON 2008
2008 July 28-30

Design of an indoor sonic boom simulator at NASA Langley Research Center

Jacob Klos
Brenda M. Sullivan
Kevin P. Shepherd
Structural Acoustics Branch
NASA Langley Research Center
Hampton VA, 23681

ABSTRACT

Construction of a simulator to recreate the soundscape inside residential buildings exposed to sonic booms is scheduled to start during the summer of 2008 at NASA Langley Research Center. The new facility should be complete by the end of the year. The design of the simulator allows independent control of several factors that create the indoor soundscape. Variables that will be isolated include such factors as boom duration, overpressure, rise time, spectral shape, level of rattle, level of squeak, source of rattle and squeak, level of vibration and source of vibration. Test subjects inside the simulator will be asked to judge the simulated soundscape, which will represent realistic indoor boom exposure. Ultimately, this simulator will be used to develop a functional relationship between human response and the sound characteristics creating the indoor soundscape. A conceptual design has been developed by NASA personnel, and is currently being vetted through small-scale risk reduction tests that are being performed in-house. The purpose of this document is to introduce the conceptual design, identify how the indoor response will be simulated, briefly outline some of the risk reduction tests that have been completed to vet the design, and discuss the impact of these tests on the simulator design.

1. INTRODUCTION

Supersonic flight over land is currently restricted due to the environmental impact of sonic booms on populations over which the aircraft would fly. These restrictions were put in place based on research performed in the 1960's that studied environmental noise and community annoyance due to conventional supersonic aircraft designs. These designs produced overpressures on the ground in the range of 1 to 3 lb_f/ft^2 during straight and level flight, which were found intrusive to people on the ground. However, there is currently a desire among airplane manufacturers to build small supersonic jets capable of overland flight by using advanced technology to mitigate boom intrusiveness [1]. A rule change would be required to allow such operation, and fundamental research into the intrusiveness of these low amplitude booms is needed before such a rule change can occur. NASA has embarked on a research program to study the intrusiveness of low amplitude sonic booms heard on the ground, and in particular inside residential houses. One element of this program is the construction of a facility that will allow researchers to systematically expose test subjects to a realistic indoor soundscape representative of indoor sonic boom exposure. This will enable researchers to develop a functional relationship between human response and the characteristics creating the indoor soundscape.

2. SIMULATOR CONFIGURATION

The configuration of the indoor sonic boom simulator consists of a room (Fig. 1) that will be constructed using typical building methods. This room will be built inside a large laboratory space at NASA Langley Research Center (LaRC). The floor plan is rectangular with dimensions of 3.66-meters (12-feet) by 4.27-meters (14-feet), with a 2.44-meter (8-foot) high ceiling. The room will be fabricated atop a raised platform (Fig. 1), where the floor of the platform will be framed with 2x10 floor joists and a 1.91-cm (¾-inch) plywood subfloor. A 0.46-meter (18-inch) crawl space under this platform will allow access to the underside of the simulator if needed. Shakers may be attached to the underside of the floor to generate floor vibration. The walls of the simulator will be constructed using 1.27-cm (½-inch) sheetrock on the interior wall surface, 2x4 stud framing, R-15 fiberglass insulation in the air cavity, and 1.27-cm (½-inch) plywood sheathing on the exterior wall surface. Siding will not be installed on the exterior walls. However, limp masses or additional sheathing may be added to the exterior wall surface to mimic mass loading effects of different exterior siding configurations. A window with a 1.22-meter (4-foot) wide by 1.52-meter (5-foot) high rough opening will be located in one of the walls (Fig. 1). Different window constructions of a common size will be interchangeable within this opening to allow examination of the effect of window design on indoor noise. The windows will be well sealed to ensure that uncontrolled rattle does not occur. A ceiling will be included, but is not pictured in Fig. 1 for clarity, and will be fabricated using 1.27-cm (½-inch) sheetrock on the interior ceiling surface, 2x6 wood rafters, R-19 fiberglass insulation in the air cavity, and 1.905-cm (¾-inch) plywood sheathing on the exterior. Two closets attached to the room will enable control of the reverberation inside the room (Fig. 1). Foam or fiberglass will be placed inside the closets and vented, louvered doors will be used for closet doors. Portions of these louvered doors will be covered or uncovered to change the size of the aperture exposing the room interior to the absorptive material inside the closets. This variation in the aperture of the closet openings will allow for systematic alteration of the room reverberation. The room will be finished with furnishings of a typical living space to give it a lived-in feeling. These furnishings, such as rugs, drapes and furniture, will also be used to control the reverberation inside the room.

3. INDOOR SOUNDSCAPE SIMULATION

The soundscape inside a residential house exposed to a sonic boom is primarily a result of two vibroacoustic phenomena. The first is transmission of the sonic boom through the structure due to the time and space dependent exterior pressure loading. The second is contact induced vibration sources that are excited at low frequency resonances by the sonic boom, but which radiate noise indoors at high frequencies due to frequency conversion caused by contact. Window rattle is an excellent example of this contact phenomenon. Both of these sources will be simulated and independently controllable in the indoor sonic boom simulator.

To simulate the transmission of the sonic boom through the structure, the room is surrounded on two sides by speaker arrays (Figs. 2 through 6). A flange (Fig. 3) is attached to the two walls that are excited by the speaker arrays. A baffled array of 0.381-meter (15-inch) diameter subwoofers is mounted to each flange (Fig. 4). Twenty-four speakers will be used in the array for the shorter wall and 28 speakers will be used in the array for the longer wall. Finally, a support structure is attached to the panels holding the speakers to add both stiffness and mass to the system exciting the walls (Figs. 5 and 6). This arrangement of baffled speakers and the flange creates an enclosed acoustic volume that is driven by the speakers (Fig. 6). This excitation system is used to create a desired pressure loading on the exterior surface of two walls of the room, which will simulate the loading that would occur on these two walls if the structure were outdoors and exposed to an actual sonic boom. Initially, a spatially uniform excitation field

will be used. However, each speaker will be individually controllable so simulation of oblique waves propagating past the structure may also be possible. This excitation system will allow researchers to study, in a controlled and repeatable environment, the transmission of different boom signatures through a typical building structure. Thus, researchers will be able to systematically isolate the effect of different boom characteristics on indoor human response.

A high stiffness and mass of the structure holding the speakers is critical to ensure that the speaker system efficiently drives the walls. Since the weight of the speaker system used to excite the walls will be substantial, it is essential that this weight not be supported by the simulator itself to avoid affecting the dynamic response of the simulators' walls. These speaker arrays will be supported by a carriage system that is attached to rails on the ceiling of the surrounding laboratory space. This will ensure that the weight is transferred to the existing laboratory and not carried by the simulator. In addition, this configuration will enable the speaker arrays to be rolled away from the simulator walls, allowing access to the exterior surface of these walls to add limp mass or additional sheathing to simulate different siding configurations.

Secondary sources that result from contact induced vibration (such as rattle, squeak and creak) will be simulated using small speakers placed inside the room. Realistic sounds will be played through these speakers; sounds will be generated either through simulation using numerical models or through measurements of rattle and other relevant noises made in controlled laboratory conditions. The apparent location of these sources can be changed by playing the sounds through speakers at different locations within the room and the intensity can be changed by varying the volume. For example, to simulate rattle coming from a window, a small speaker will be placed near the window and rattle-like sounds will be played through the speaker. Simulation of secondary sources in this manner, using speakers, will enable repeatable control of the level and spectra of these different sources. This will enable researchers to systematically isolate the effect of secondary sources on indoor human response.

4. LESSONS LEARNED FROM RISK REDUCTION TESTING

The excitation system that will be used to drive the walls to simulate transmission of the boom into the interior is the core technical challenge in the design of the simulator's structure. Many different risk reduction tests have been performed over the course of the past year to both assess the feasibility of, and address issues arising from, the design for simulating boom transmission through the structure. An overview of the tests and some of the lessons learned from those tests are documented here.

All of the risk reduction tests were carried out on a scale version of one wall of the indoor sonic boom simulator. This test box is illustrated in Figs. 7 and 8, and consists of a 3 by 3 array of 0.381-meter (15-inch) diameter subwoofers that are mounted into a panel that is stiffened by a wood frame (Fig. 7). The test box is 2.43-meters (96-inches) wide by 1.52-meters (60-inches) tall and has a flange that is 0.304-meters (12-inches) deep (Fig. 8). A wood blank is clamped into the flange of the test box to form an enclosed acoustic cavity (Fig. 7) that is driven by the speakers. The wood blank mimics one of the excited walls of the full-scale indoor sonic boom simulator (Fig. 6). Microphones are mounted in several thru holes in the wood blank (Figs. 7 and 9) to sense the pressure response inside the acoustic cavity at the interior surface of the wood blank due to excitation from the speakers. The microphones are sealed in the holes using o-rings. Each speaker can be driven independently of the others, and results are presented here for coherent pink noise excitation of the nine speakers. This test box has been used to investigate the affects of the coupled structural acoustic system formed by the wood blank and the air cavity.

A section view of the full-scale simulator and excitation system is illustrated in Fig. 6. The acoustic cavity that is formed between the exterior surface of the walls of the simulator and the panels holding the speakers is identified in Fig. 6. This cavity is similar to the one that is formed between the speakers and the wood blank in the risk reduction test box (Fig. 7c). It is anticipated that this empty acoustic cavity will be very resonant; thus, an acoustic treatment to control the modal response of this acoustic cavity was sought. Several treatment configurations have been tested and will be thoroughly documented in a future publication. The treatment configuration for this cavity that has proven most beneficial is a wooden baffle system lined with fiberglass, which is installed in the flange (Fig. 10). This treatment is effective at eliminating the modal response that is associated with the 2.43-meters (96-inches) width and 1.52-meters (60-inches) height of the test box. The addition of the fiberglass to the baffled system also reduces the modal response that is associated with the width and height of the individual baffled volumes. As well as reducing the modal response of the acoustic cavity, the baffle also reduces the crosstalk between speakers. When considering the pressure response measured by a microphone placed in the wood blank in front of one of the speakers (Fig. 9), the contribution at that microphone from a neighboring speaker is at least 10 dB lower than the contribution from the collocated speaker. A similar system of baffles and absorptive material will be used inside the flange of the full-scale simulator.

One issue that has hindered progress of the conceptual design is the strong coupling of the first few mechanical resonances of the excited structure, in this case the wood blank, and the acoustic stiffness created by the enclosed air volume. Due to the high stiffness of the acoustic volume at low frequencies, and the efficient coupling of this stiffness to the low order modes of the structure, the excited structure does not respond to transient or forced excitation as it would if the acoustic volume were absent. However, it has been found that the introduction of a substantial leak (Fig. 11) into the acoustic volume formed inside the flange reduces the coupling of the mechanical structure and acoustic stiffness, allowing the structure to respond freely. However, the introduction of a leak negatively affects the low frequency performance of the speaker arrays, limiting the pressure amplitude that can be created inside the cavity. A simple case study is presented below.

Two types of leaks have been introduced in the risk reduction test box, and their effect on the structural response and drive system is documented here. Two 10-cm (4-inch) diameter holes were made next to each of the nine speakers (Fig. 11a), eighteen holes in total. In addition, a gap between the flange and speaker array (Fig. 11b) can be introduced to vent the acoustic cavity to ambient. Each of these holes (Fig. 11a) can be covered and the size of the gap (Fig. 11b) can be varied, or eliminated, to demonstrate the effect the leak size has on the response of the structure and drive system. To identify the sensitivity of the structural response to the size of the leak, the drive point mobility of the wood blank was measured using a shaker and impedance head (Fig. 12) for four different size leaks. These drive point mobility measurements are illustrated in Fig. 13. When a large leak is introduced, the drive point mobility approaches the mobility of the wood blank still clamped in the flange but located in free space (Fig. 13). The drive point impedance for the case when all 18 holes are open and a 4" gap around the boundary is introduced (Fig. 13, dash-dot line) is very similar to the drive point impedance for the wood blank located in free space (which is not shown). When the size of the leak is reduced, the drive point mobility is affected by the cavity stiffness (Fig. 13, dashed and solid lines). From these simple tests, it can be concluded that it is essential to create an excitation mechanism that weakly couples the structural and acoustic systems. If this is not done, the structure will not respond to excitation as it would if located in free space due to the acoustic stiffness formed by the enclosed

acoustic cavity. Thus, to simulate the transient response of a wall exposed to a simulated sonic boom pressure excitation, an appropriately sized leak must be introduced in the acoustic cavity.

The influence of the leak size on the actuation authority of the drive system was investigated by measuring the transfer function between the drive voltage to the speaker amplifiers and the pressure response at a microphone mounted in the wood blank. Ideally, this transfer function would be smooth with respect to frequency, and would not contain any strong resonances or anti-resonances. Transfer functions for four different leak sizes are presented in Fig. 14 for coherent excitation of the speakers. The strong coupling of the structural and acoustic systems is evident by the sharp notch formed in the first two curves presented in Fig. 14 (for the sealed cavity and nine 4-inch holes). The presence of this notch would make implementation of an equalization system [2] difficult. As the size of the leak is increased, the transfer function becomes better behaved. However, when a leak is introduced the pressure that can be created at the surface of the wood blank, for a unit voltage excitation to the amplifiers, is significantly reduced. Thus, the low frequency actuation authority of the drive system is reduced.

5. CONCLUSIONS

A conceptual design for an indoor sonic boom simulator has been developed by NASA personnel and construction of the simulator is planned to start during the summer of 2008. Completion of the construction should occur sometime in late 2008. Once completed, several months will be spent vetting the excitation system that will be used to simulate the transmission of booms through the structure. Lessons learned from the small-scale risk reduction tests will be incorporated into the full-scale simulator.

With a drive system that incorporates leaks in the acoustic cavity, reproducing the very low frequency content of sonic booms will not be possible. However, the purpose of this simulator is to reproduce a realistic audible soundscape for subjective testing. Excitation of the structure in the infrasonic range, well below the first resonant mode of the structure, is not required to simulate the audible response inside a building exposed to sonic booms. Thus, the desired pressure loading on the exterior walls of the full-scale simulator will be high pass filtered with a cutoff frequency slightly below the first resonant mode of the structure, which is expected to be between 10 and 20 Hz. In the full-scale simulator, the design challenge is to introduce an appropriately sized leak that enables enough actuation authority to create the desired pressure excitation and which still yields a structural response that is similar to what it would be if the walls were in free space. Tests performed to date would indicate that this task is possible.

All of the risk reduction testing to date has focused on the issues related to simulating the transmission of the boom through the structure. Simulations of rattle and other contact induced noises will be incorporated into the interior soundscape simulation once the simulator is built.

REFERENCES

[1] K.J. Plotkin, J.A. Page, D.H. Graham, J.W. Pawlowski, D.B. Schein, P.G. Coen, D.A. McCurdy, E.A. Haering, J.E. Murray, L.J. Ehernberger, D.J. Maglieri, P.J. Bobbitt, A. Pilon, J. Salamone, "Ground Measurements of a Shaped Sonic Boom", Proceedings of the 10th AIAA/CEAS Aeroacoustics Conference, Paper number AIAA 2004-2923, 2004.

[2] Brown, Donald E.; and Sullivan, Brenda M.: "Adaptive Equalization of the Acoustic Response in the NASA Langley Sonic Boom Chamber" : Proceedings, International Conference on Recent Advances in Active Control of Sound and Vibration, VPI & SU, Blacksburg, Virginia, April 15-17,1991 pp. 360-371.

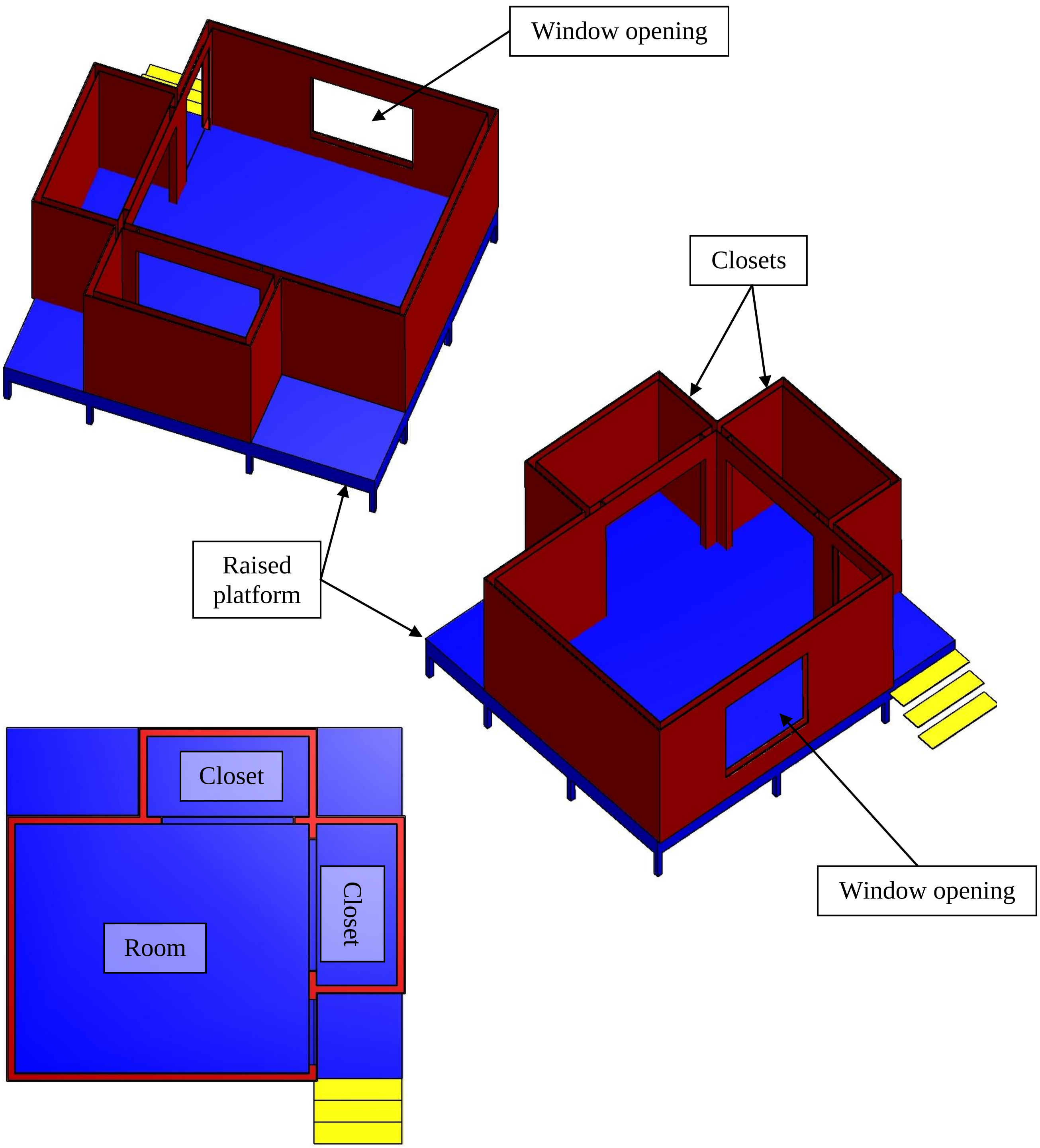

Figure 1: Three views of the structure of the simulator (ceiling has been removed for clarity).

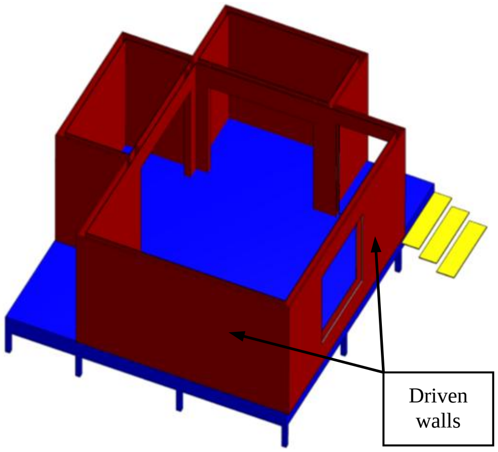

Figure 2: The simulator structure.

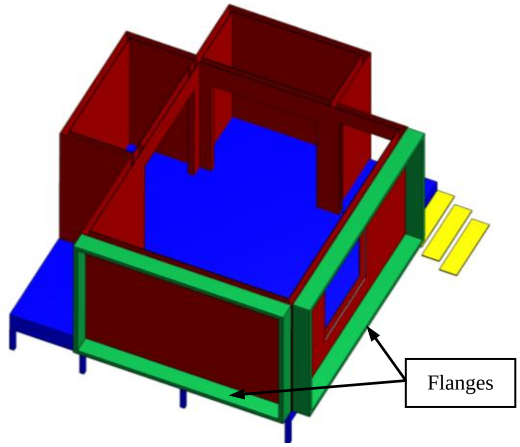

Figure 3: Flange attached to the outside of the walls that are excited.

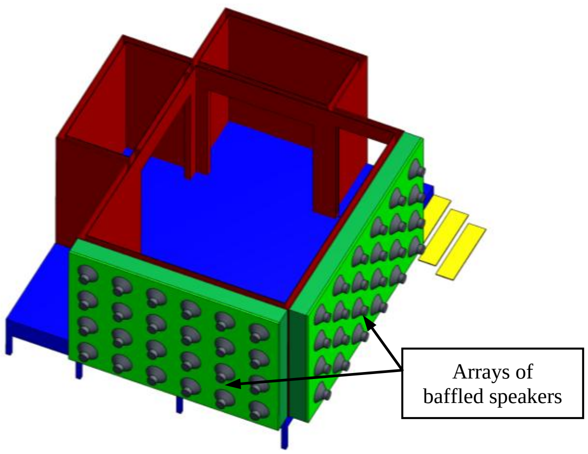

Figure 4: Speaker array butted up to the flange, creating an air cavity between the speakers and the wall surface.

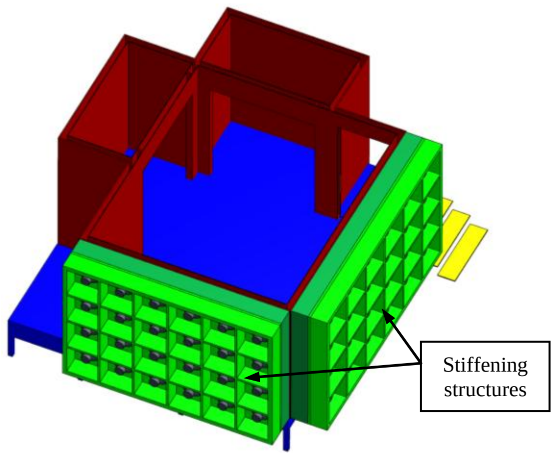

Figure 5: Frame attached to the panel holding the speakers to add stiffness and mass to the speaker support.

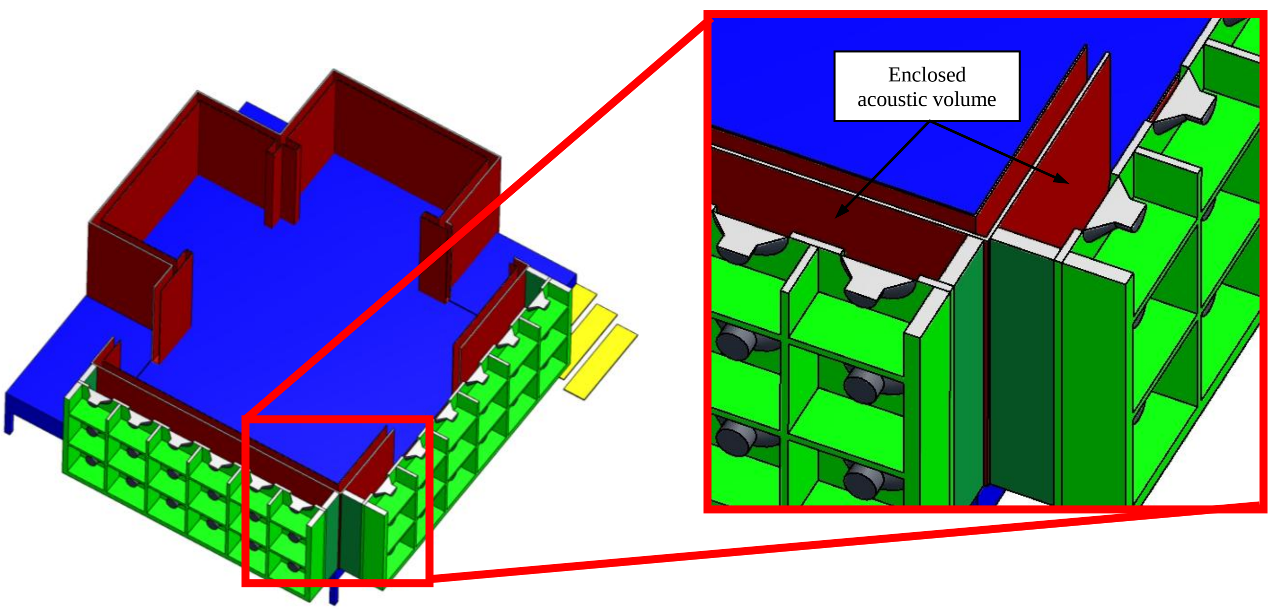

Figure 6: Section view of the simulator and speaker system illustrating the acoustic cavity formed between the speaker system and the exterior surface of the walls.

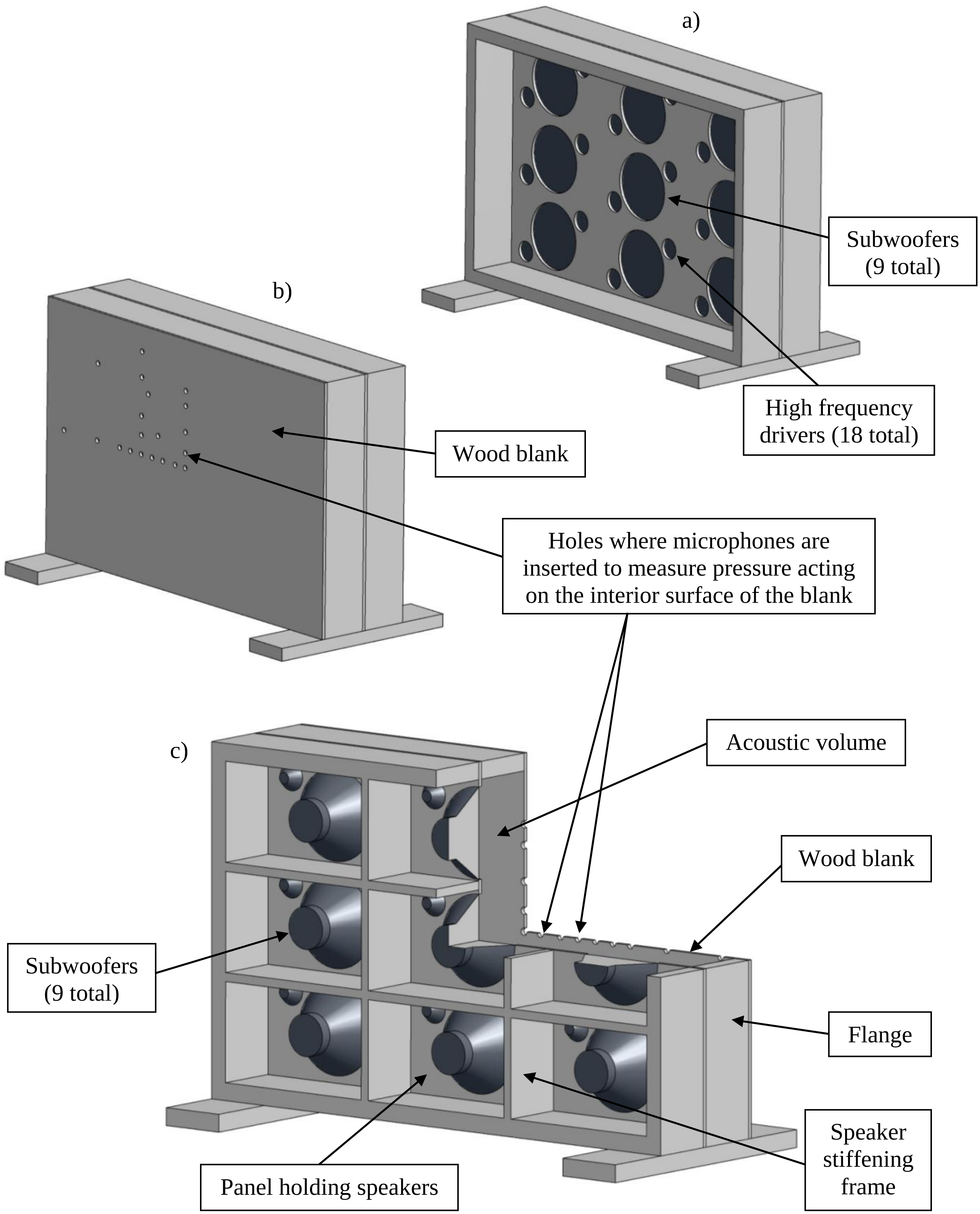

Figure 7: Risk reduction test box showing the box with and without the wood blank; a) front view of the test box without wood blank installed, b) front view of the test box with the wood blank installed and c) sectioned rear view of the test box with wood blank installed.

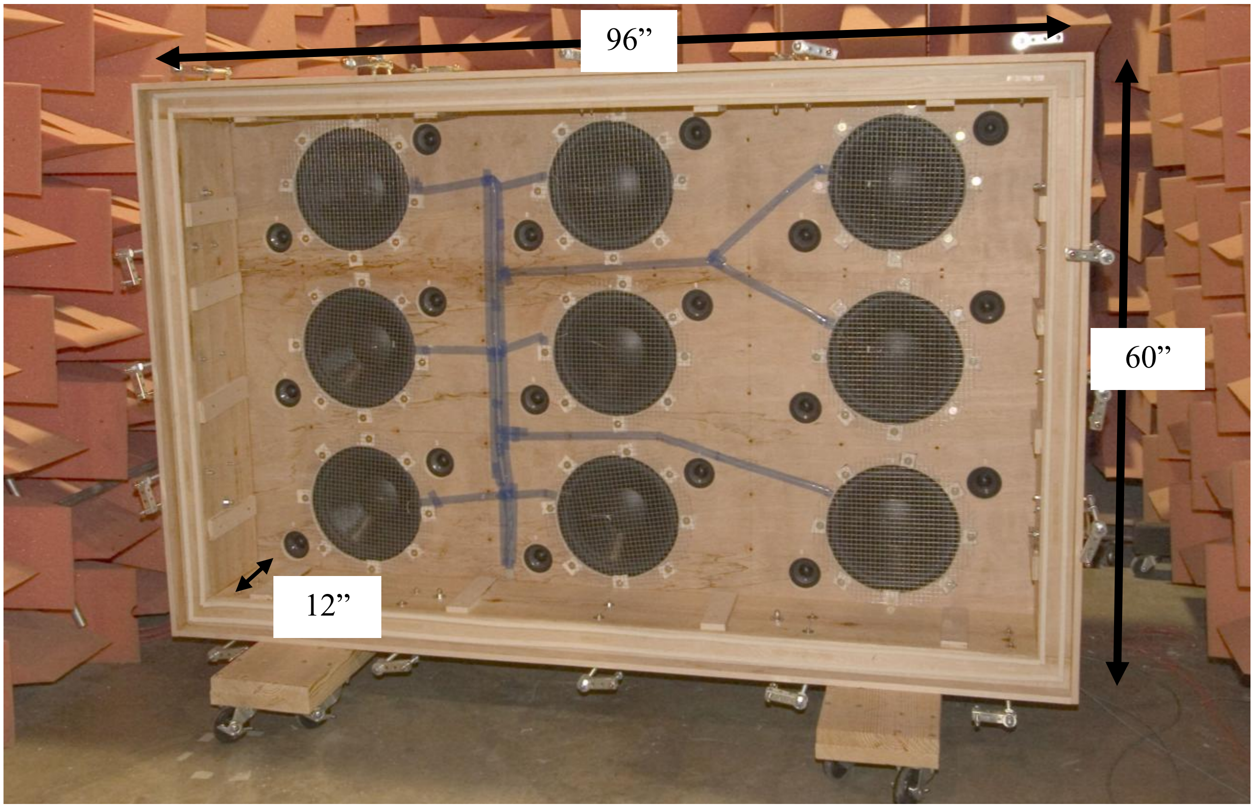

Figure 8: Photograph of the risk reduction test box without the wood blank installed and without the baffled treatment.

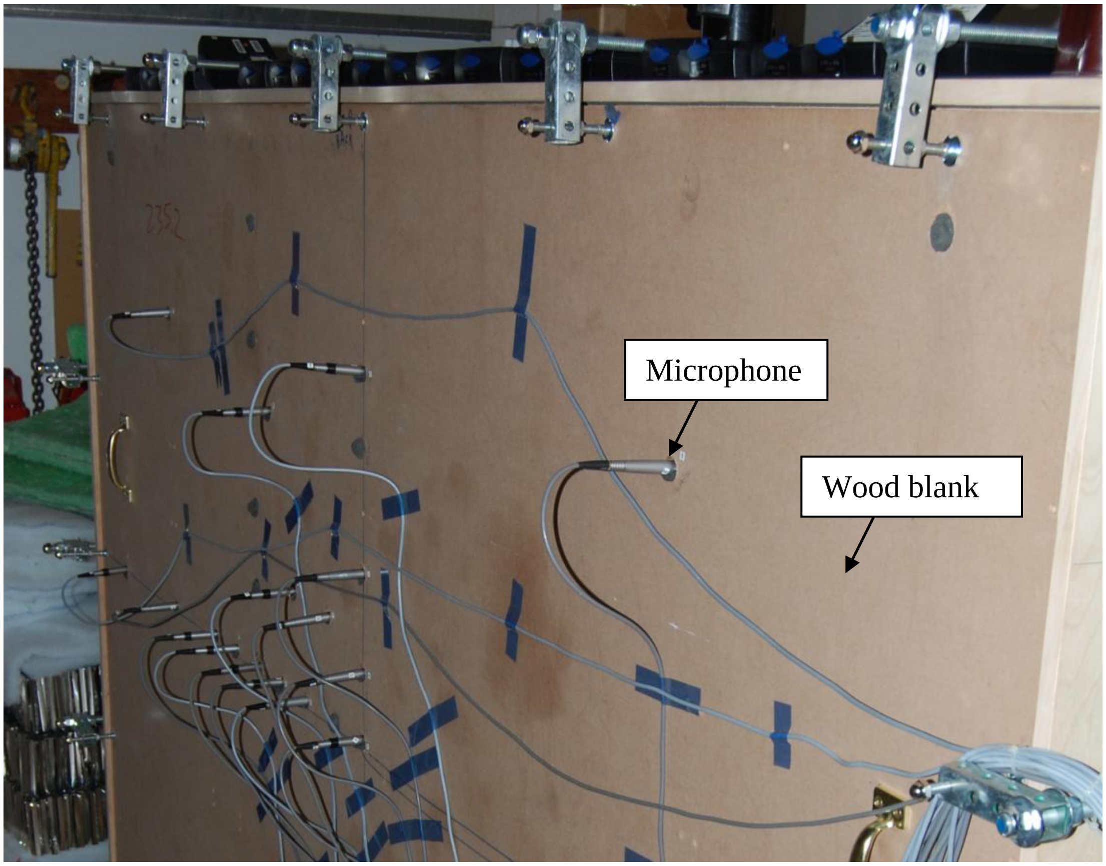

Figure 9: Wood blank with microphones installed.

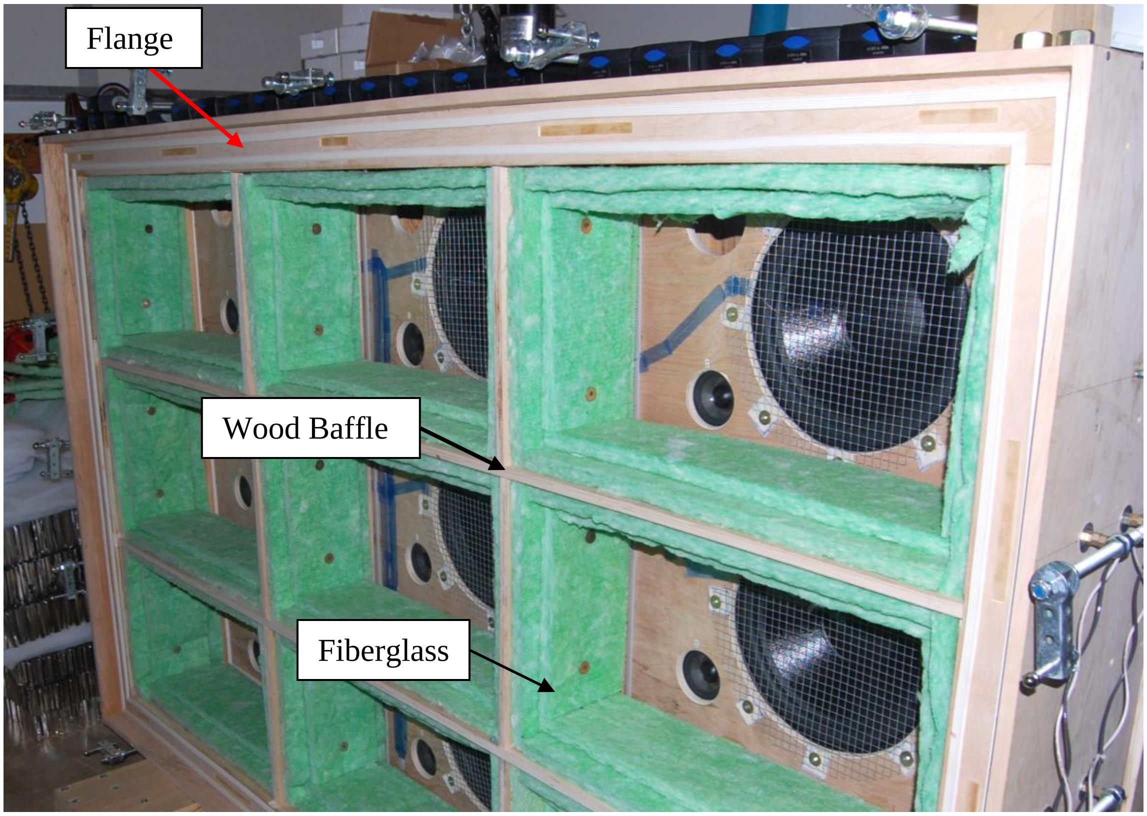

Figure 10: Baffles and treatment inside the flange of the risk reduction test box.

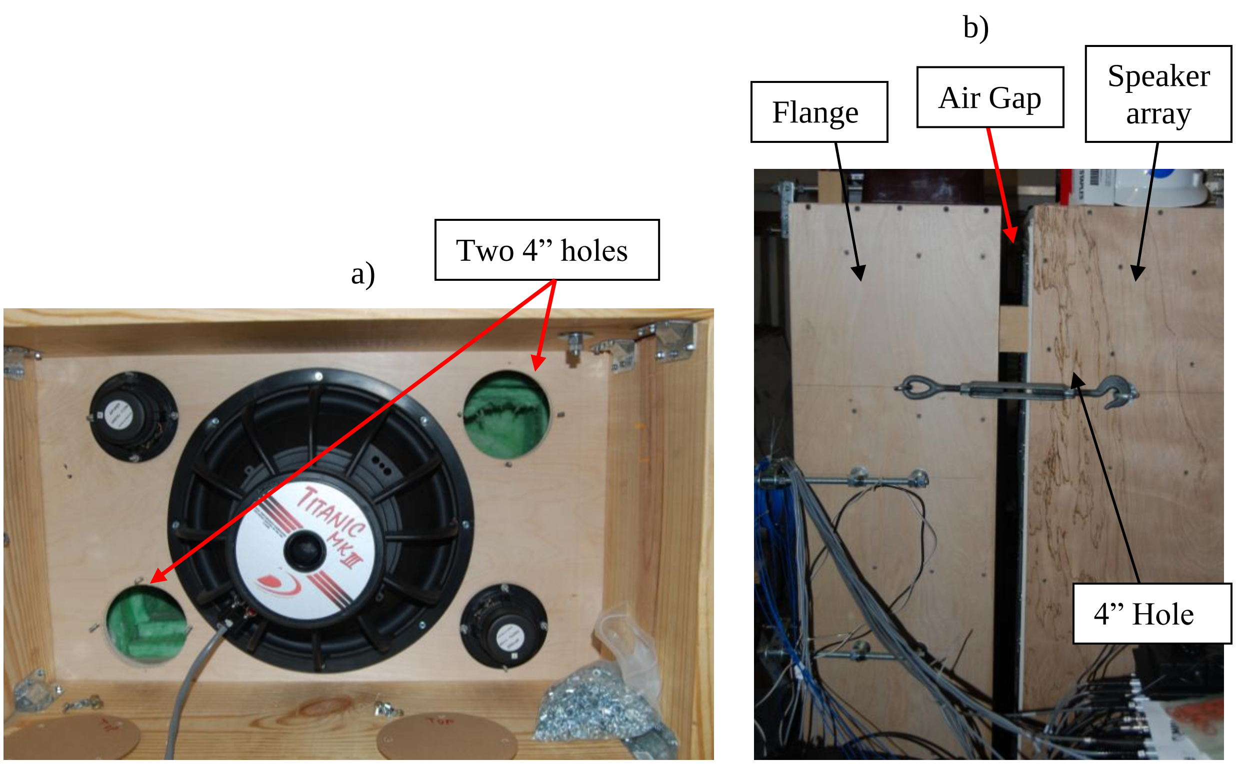

Figure 11: The types of leaks introduced in the air cavity to alter the coupling of the structural and acoustic systems; a) 4-inch diameter holes in the panel holding the speakers (one speaker shown) and b) gap in the interface between the flange and speaker array frame.

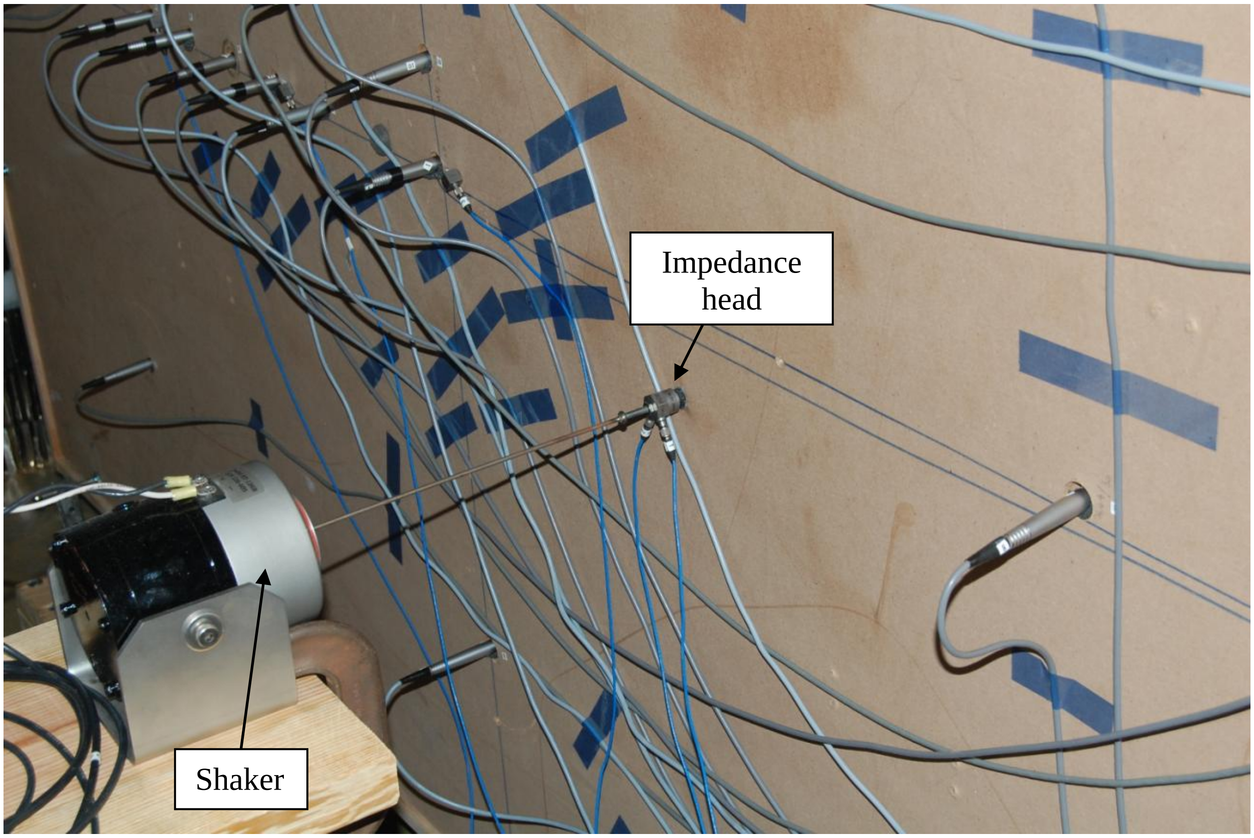

Figure 12: Drive point mobility measurement of the panel using a shaker and impedance head.

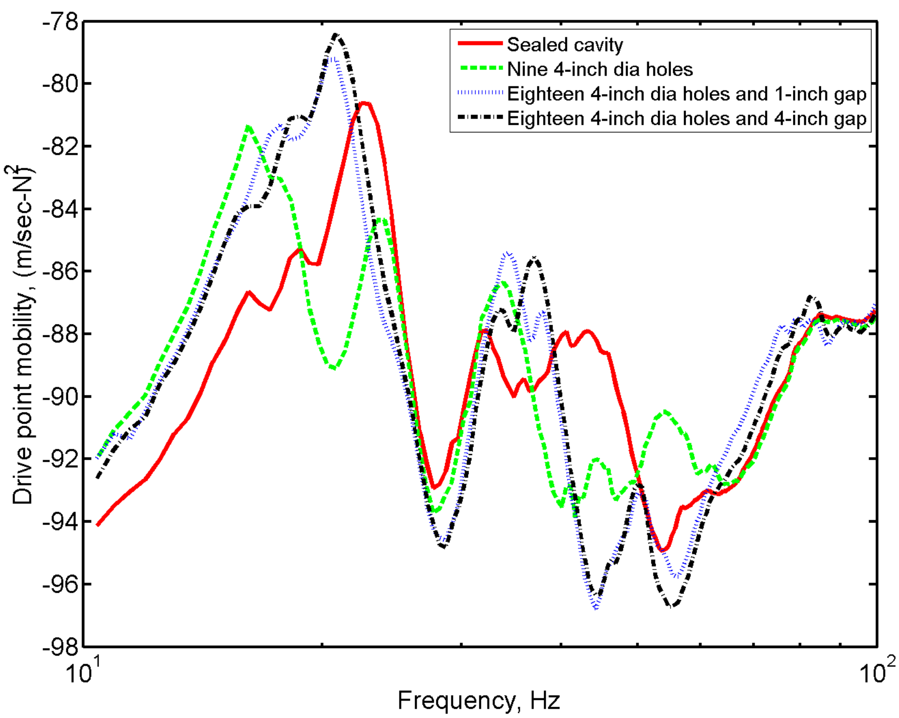

Figure 13: Drive point mobility of the wood blank when different size leaks are introduced into the acoustic cavity.

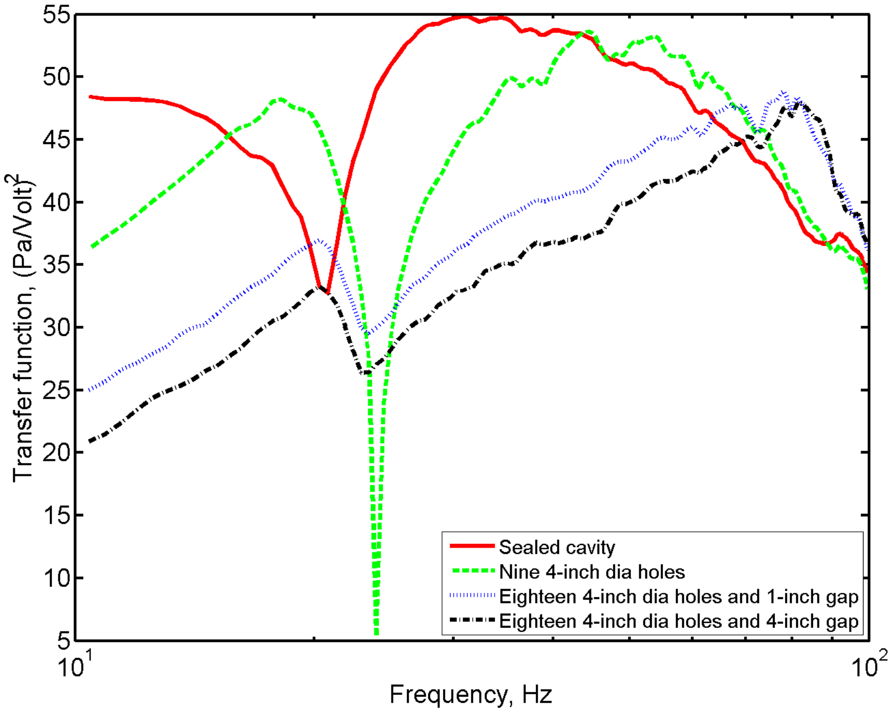

Figure 14: Transfer function between the amplifier drive signal and the pressure at the interior surface of the wood blank for coherent speaker excitation when different size leaks are introduced into the acoustic cavity.